Precision Measurements and Charged Lepton Flavor Violation

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Marina Artuso/ Syracuse
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TG 3/5 Conveners:

Precision Measurement and Small Experiments:

Tom Blum (U Conn) and Peter Winter (ANL)

Charged Lepton Flavor Violation:

Sacha Davidson (Lyon) and Bertrand Echenard (Caltech)

Standard Disclaimer

- I can't cover everything and if I left your favorite topic out I apologize; please bring it up in questions.
- Ideas and good work belong to so many people, but mistakes are all mine

I will try to do better!

LOI Comments

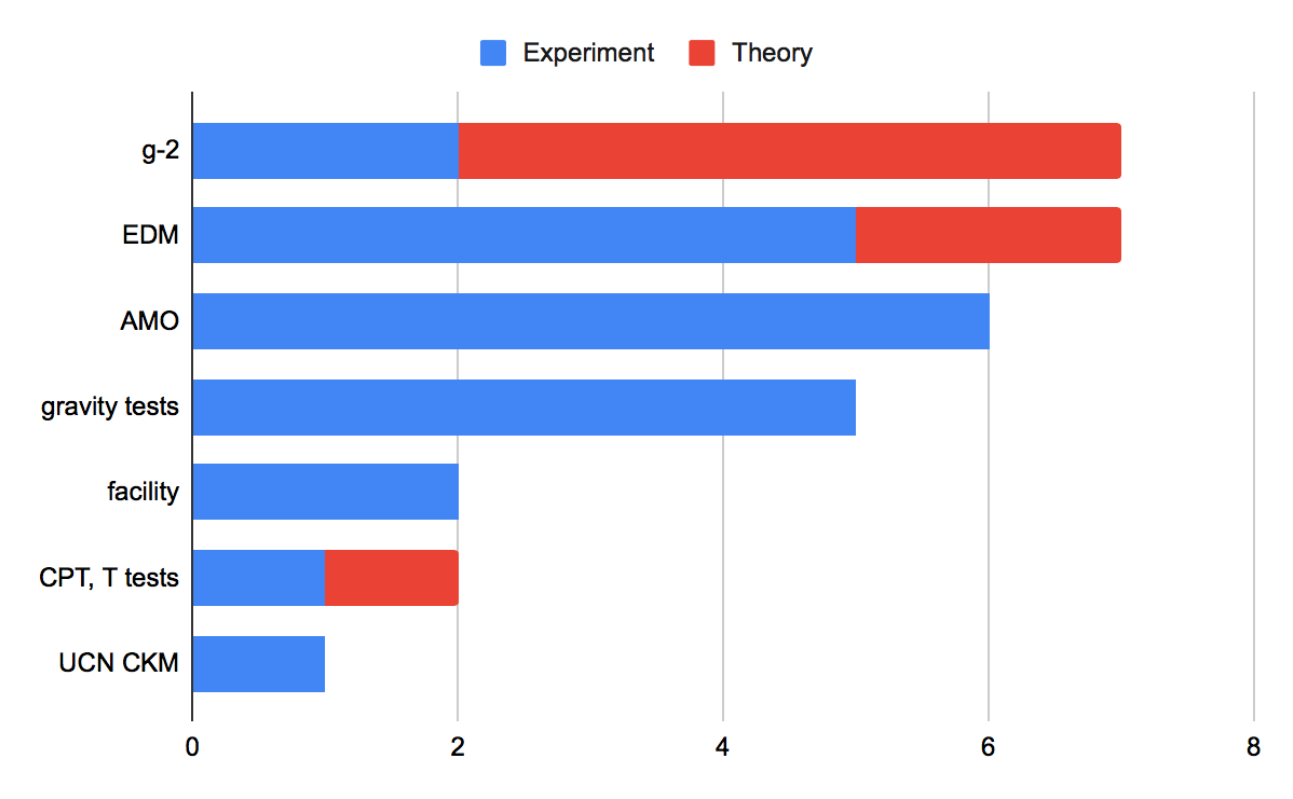
- # of LOIs is not a good proxy for community interest but it's easy/convenient to do that
  - some large groups submitted small numbers of LOIs, some LOIs were on a restricted topic
- *we're looking for general themes*
- *that's what I want you to carry away*

New Cross-Frontier Efforts

- White Papers don't need to be based on your existing LOIs
- A main point of this meeting is generating cross-talk!
- If something interests you and it's cross-topical group or cross-frontier, please go for it!
  - you will see several examples: AMO/RPF, joint EF/RPF and cross RPF workshops

Precision Measurements (TG3)Topics

- Precision Measurements in “Small” Experiments



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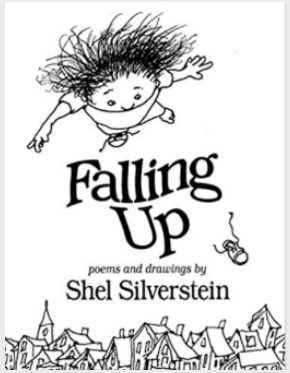
LOI Breakdown

"Fundamental" Physics	
Dedicated Experiment Exploring Gravitational Effects on CP Violation	Gravity-generated / connected CPV
Strong CP and Neutrino Masses: A Common Origin of Two Small Scales	neutron EDM <-> neutrino masses (cross-frontier)
Searches for Exotic Short-range Gravity and Weakly Coupled Spin-Dependent Interactions using Slow Neutrons	Gravity tests with neutrons
Lorentz and CPT Tests with Low-Energy Precision Experiments	L / CPT tests (overview of many opportunities)
NOPTREX:	T violation with neutrons
Muonium Gravity Experiment	Gravity test (antimatter)
Facilities	
Upgraded Low-Energy Muon Facility at Fermilab	Facility (cross-group)
Potential storage ring and Muon Campus experiments	Muon campus / facility use
Dipole Moments	
Using lattice QCD for the hadronic contributions to the muon g – 2	Lattice QCD - HVP
Calculations of nucleon electric dipole moments on a lattice with chiral fermions	Lattice QCD - nucleon EDM
Hadronic contributions to the anomalous magnetic moment of the muon	Lattice QCD - HVP & HLbL
Opportunities and New Physics Implications for (g – 2)e,μ	electron and muon MDM: Theory model (cross frontier)
The Proton Storage Ring EDM Experiment	EDMs (CPV) and axion DM
Test of the Standard Model and Search for Physics Beyond∗ Opportunities for Fundamental Physics using Small-scale Storage Ring Experiments	EDMs storage ring (see other LOI in AF5)
Direct measurement of short-lived particle dipole moments at the LHC	MDM at LHC

AMO	
Atomic/nuclear clocks and precision spectroscopy measurements for dark matter	Precision clocks and spectroscopy/DM
Optically levitated sensors for precision tests of fundamental physics	Gravity tests (micron-scale) with nanospheres, axion DM
Probing fundamental physics with highly-coherent nuclear spins	EDM (CPV) and axion DM
Th-229 Nuclear Clock	Precision clocks
Mechanical tests of the gravity-quantum interface	Gravity (-quantum) tests
Doped Cryocrystals for Ultrasensitive EDM Measurements: Snowmass LOI	EDMs, facility for cryo-crystals
Searches for new sources of CP violation using molecules as quantum sensors	EDMs (CPV) with molecules

Summary of LOIs and Workshop

- Workshop on Electric and Magnetic Dipole Moments (15-17 Sep)
- After reading these and attending workshop, we see a strong interest in:
  - muons
    - general facility for μSR and low-energy experiments
    - EDMs and MDMs (and EDM from g-2, proton storage ring)
  - "fundamental physics"
    - gravity/antigravity and CPT tests



Major Improvements Soon!

- Multiple facilities, methods, and even sub-fields!

Great Future Expectations

- **$d_n \rightarrow 10^{-27}$-10^{-28} e-cm Neutron Spallation/Reactor Sources**
- **$d_e \rightarrow 10^{-30}$ e-cm or better! (Molecules) ACME**
- **d_p & $d_D \rightarrow 10^{-29}$e-cm Storage Ring Proposal (BNL/COSY)**

Pave the way for a new generation of storage ring experiments d_e, d_p, d_D, d(^{3}He), d(radioactive nuclei), d_μ

Several orders of magnitude improvement expected

All Very Well Motivated – Must Do Exps.

13

Marciano MDM/EDM Workshop

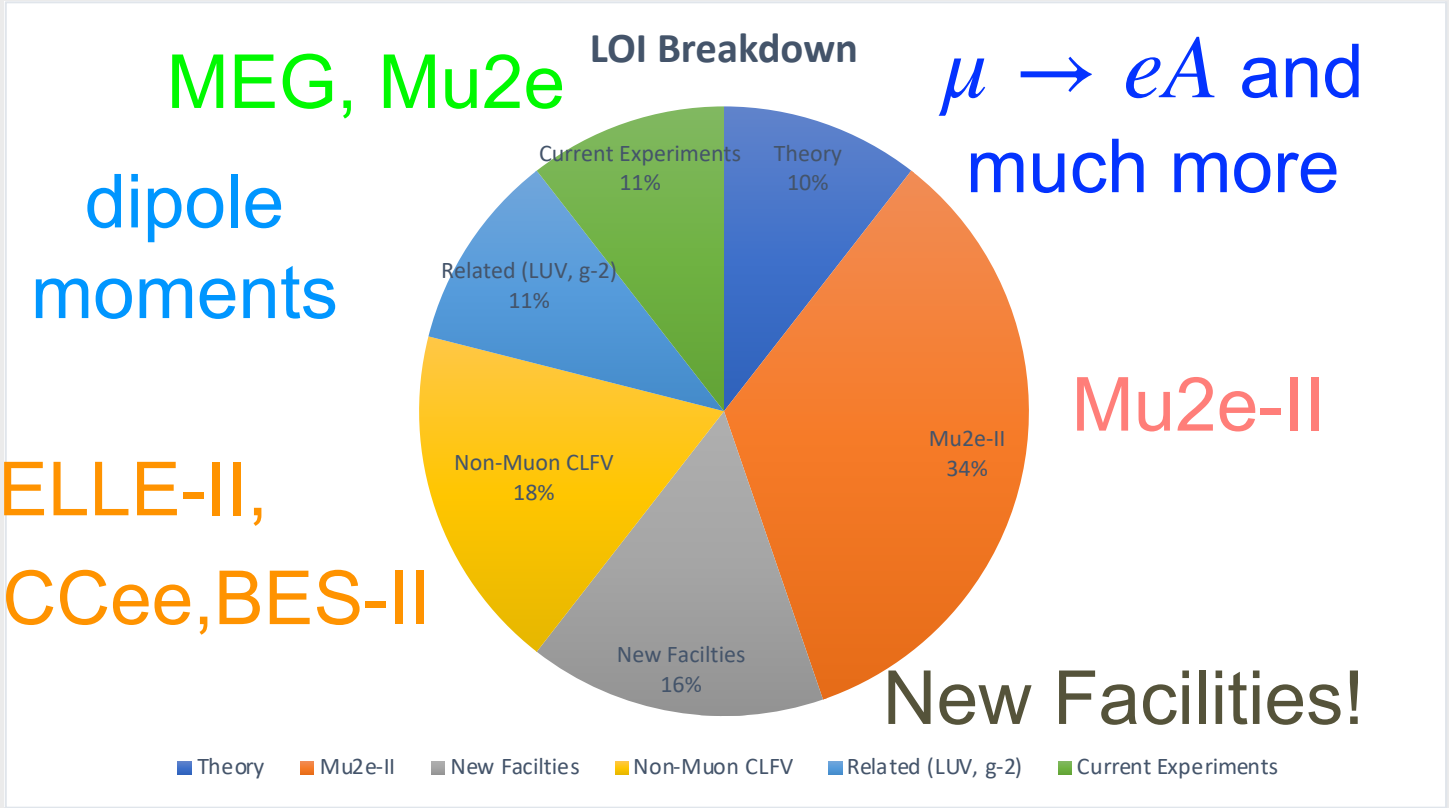
- We need to grasp how these relate to each other

AMO

- This is very exciting and just what should come out of Snowmass
- Some members of AMO community interested in partnership
  - analogy to DNP "fundamental symmetries". Is this group like Fundamental Symmetries in DNP?
    - DNP people (see PIENU LOI, QWeak,…) have always overlapped, moved back and forth; shared interests and culture
  - What are the complementarities? Are there places (proton EDM for example) where AMO is better? How do you quantify this?
  - This is something new; this topical group is the place to understand it.
    - HEP meets AMO workshop planned!

Charged Lepton Flavor Violation (TG5) LOIs

- 38 Total
- Several interlinked LOIs on future muon program, linked to TG3



Charged Lepton Flavor Violation Activities and Cross-Links

- Series of Workshops:
  - muon decays: 10^5 *TeV mass scales (dim-6)*
  - tau decays
  - heavy quarks (organized with RPF's TG1)
  - heavy states (Higgs, Z, W, exotics organized with EF)
- CLFV and LUV
  - this is important given LHCb, etc. results. The two are linked in ways we don't understand

Theory LOIs

- Light new physics, muonium-antimuonium, and $\Delta L = 2$ ($\mu^- N \rightarrow e^+ N^*$): relation to $0\nu2\beta$

Theory
Physics of muonium and anti-muonium oscillations
physics potential with MEGII-fwd
Possibility of Search for Bound μ− → e−a Decay
Rare muon decays and light new physics
Search for Muon to Positron Conversion in μ− → e− Conversion Experiments
Searching for μ− → e+ Conversion at Upcoming Experiments and the Process of Radiative Muon Capture
Theory challenges and opportunities of Mu2e-II

New Programs

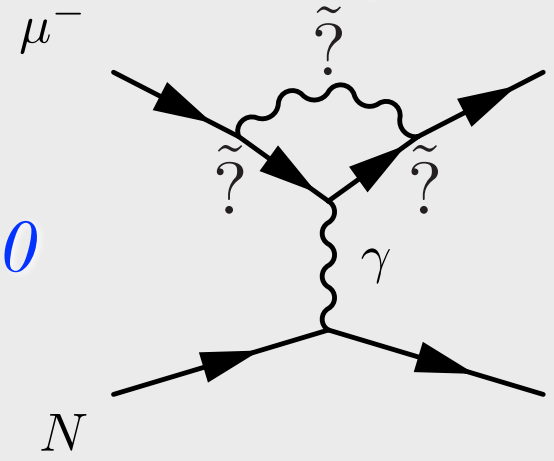
- Mu2e-II (x10 Mu2e) is under active development
- Between TG3/5 there seems to be a groundswell for investigating a muon program at PIP-II: *links to muon collider and neutrino factories*

Upgraded Low-Energy Muon Facility at Fermilab
A New Charged Lepton Flavor Violation Program at Fermilab
A Phase Rotated Intense Source of Muons (PRISM) for a μ → e Conversion Experiment
Bunch Compressor for the PIP-II Linac
A new experiment for the μ → eγ search
Search for Muonium to Antimuonium Conversion

Muons: Effective Lagrangian

$$\mathcal{L}_{\mathrm{CLFV}} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma_\mu u_L + \bar{d}_L\gamma_\mu d_L)$$

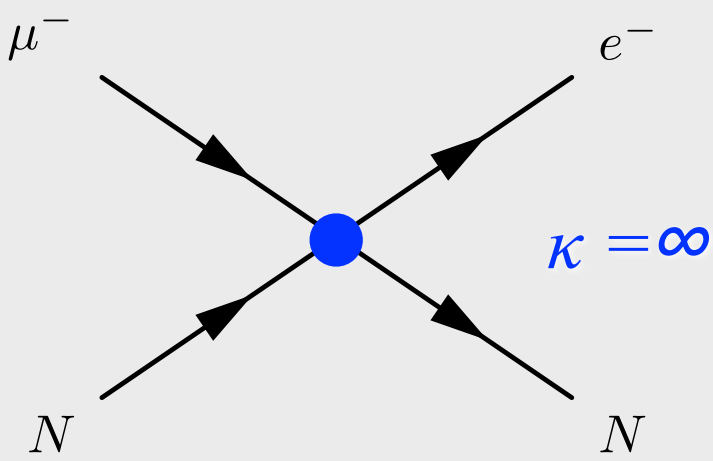
"Loops"



$\kappa = 0$

mass scale Λ

κ



$\kappa = \infty$

"Contact Terms"

Supersymmetry and Heavy Neutrinos

Contributes to $\mu \to e\gamma$

(just imagine the photon is real)

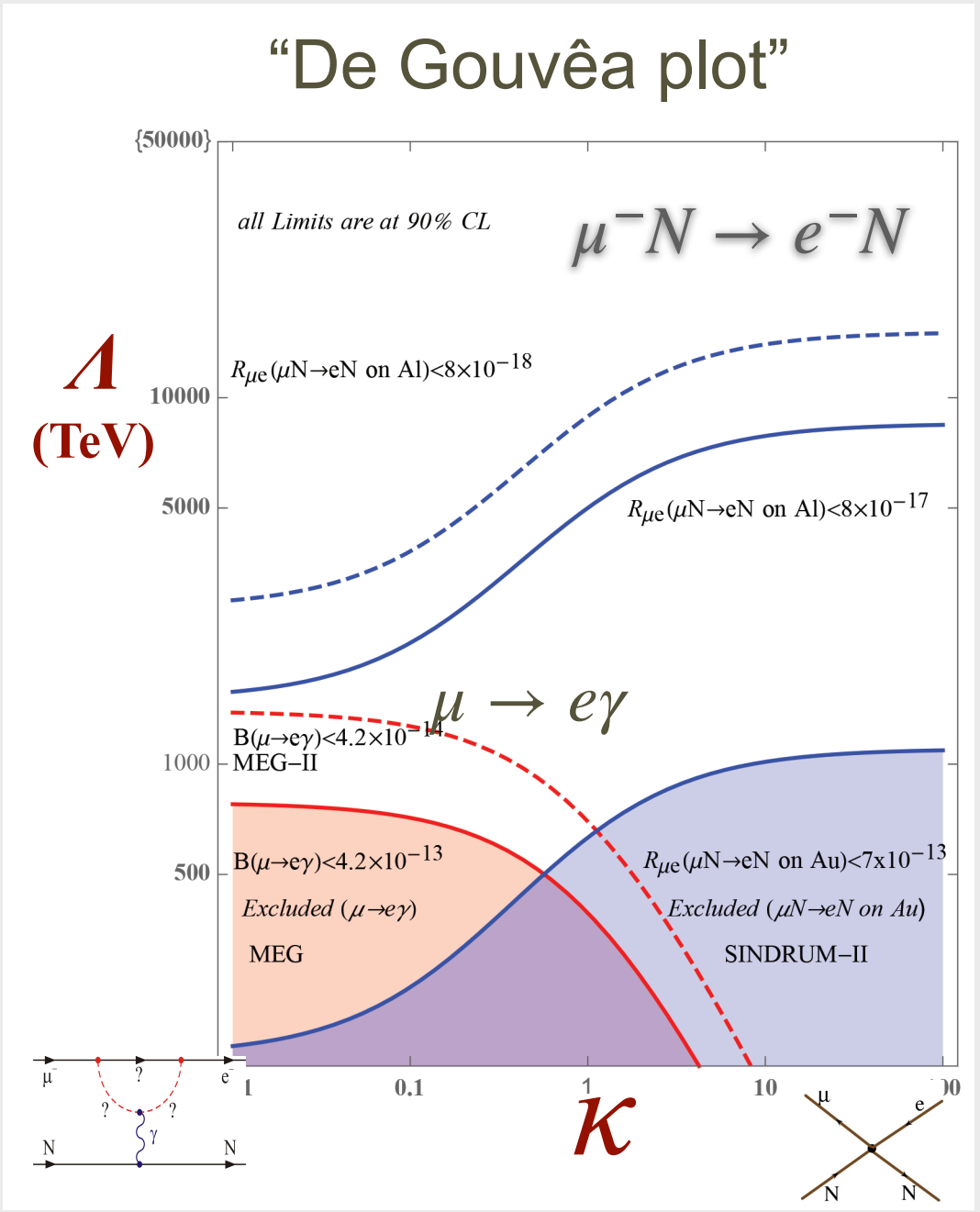
New Particles at High Mass Scale (leptoquarks, heavy Z,...)

Does not produce $\mu \to e\gamma$

Comparing Gives More Information!
(EFT vs Top Down, sessions 125/126)

μe Conversion and $\mu \rightarrow e\gamma$

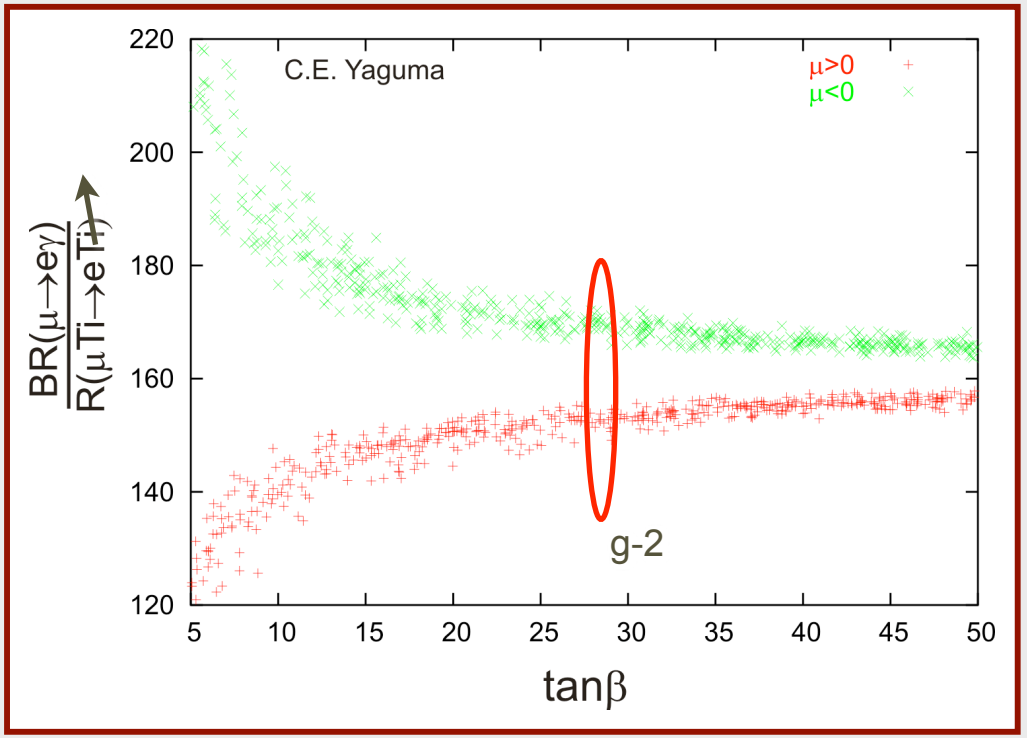
- MEG/Mu2e/ COMET/Mu3e probing $10^3 - 10^4$ TeV mass scales
- Upgrades at MEG, Mu2e-II are an *additional* x10-100, x2-3 in mass for dim-6
- Mu3e ($\mu \rightarrow 3e$) also spans entire range in κ



Interconnection Among Measurements

Yaguna,
hep-ph/0502014v2

MSSM w mSUGRA



sign of μ!
from CLFV
and MDM

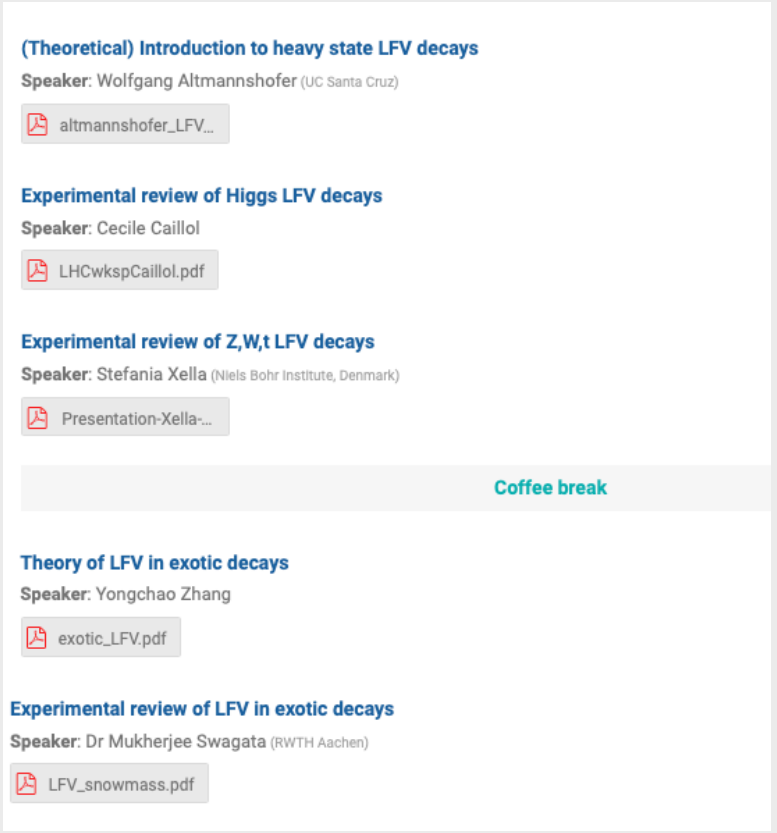
- Need:
  - observation of CLFV in more than one channel, and/or
  - evidence from LHC, g-2, or elsewhere

to allow discrimination among different models

CLFV Heavy State Decays

- Workshop 3 Sept

- Lepton flavor violating decays of Z, Higgs, top are clear signatures of NP.
- With the expected experimental sensitivities one can probe NP scales in the 1 - 10 TeV range.
- Often strong indirect constraints from low energy lepton flavor violating processes ($\mu \to e\gamma$ etc.), but in many cases there is complementary sensitivity to the NP.



(Theoretical) Introduction to heavy state LFV decays
Speaker: Wolfgang Altmannshofer (UC Santa Cruz)
altmannshofer_LFV...

Experimental review of Higgs LFV decays
Speaker: Cecile Caillol
LHCwkspCaillol.pdf

Experimental review of Z,W,t LFV decays
Speaker: Stefania Xella (Niels Bohr Institute, Denmark)
Presentation-Xella-...

Coffee break

Theory of LFV in exotic decays
Speaker: Yongchao Zhang
exotic_LFV.pdf

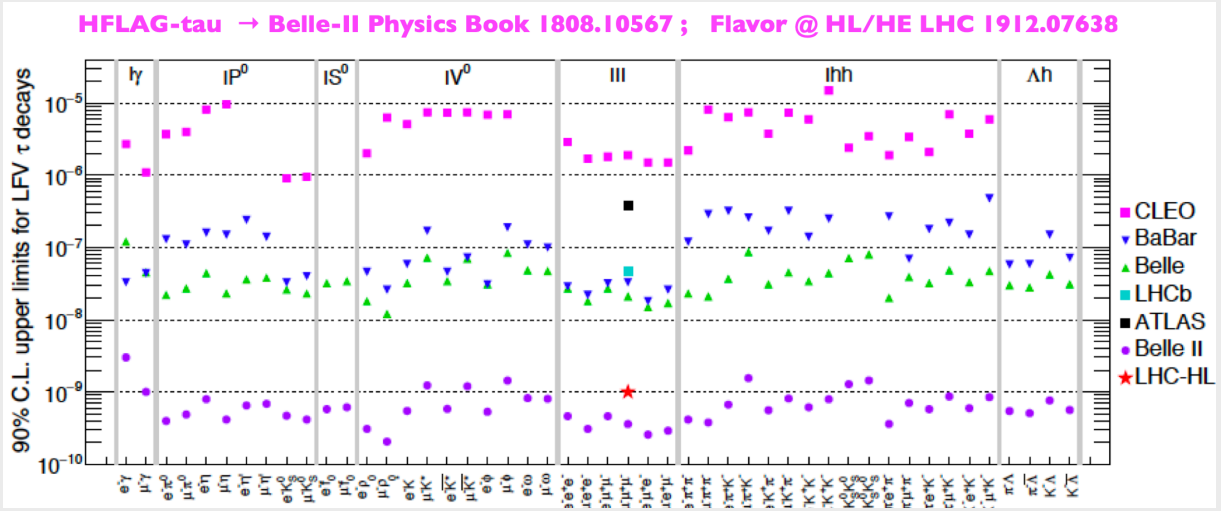
Experimental review of LFV in exotic decays
Speaker: Dr Mukherjee Swagata (RWTH Aachen)
LFV_snowmass.pdf

Altmanshoffer

CLFV in Taus

- Very broad portfolio, 1-2 order of magnitudes expected
- τ effects can be quite large and these are compelling measurements

x100



	$\tau \to 3\mu$	$\tau \to \mu\gamma$	$\tau \to \mu\pi^+\pi^-$	$\tau \to \mu K\bar{K}$	$\tau \to \mu\pi$	$\tau \to \mu\eta^{(\prime)}$	•••
$O^{4\ell}_{S,V}$	✓	–	–	–	–	–	
O_D	✓	✓	✓	✓	–	–	
O^q_V	–	–	✓	✓	–	–	
O^q_S	–	–	✓	✓	–	–	
O_{GG}	–	–	✓	✓	–	–	
O^q_A	–	–	–	–	✓	✓	
O^q_P	–	–	–	–	✓	✓	
$O_{G\tilde{G}}$	–	–	–	–	–	✓	

••• Tree-level contributions to τ→μ processes from low-scale operators Celis-VC-Passemar 1403.5781

probing many effective operators

Cirigliano

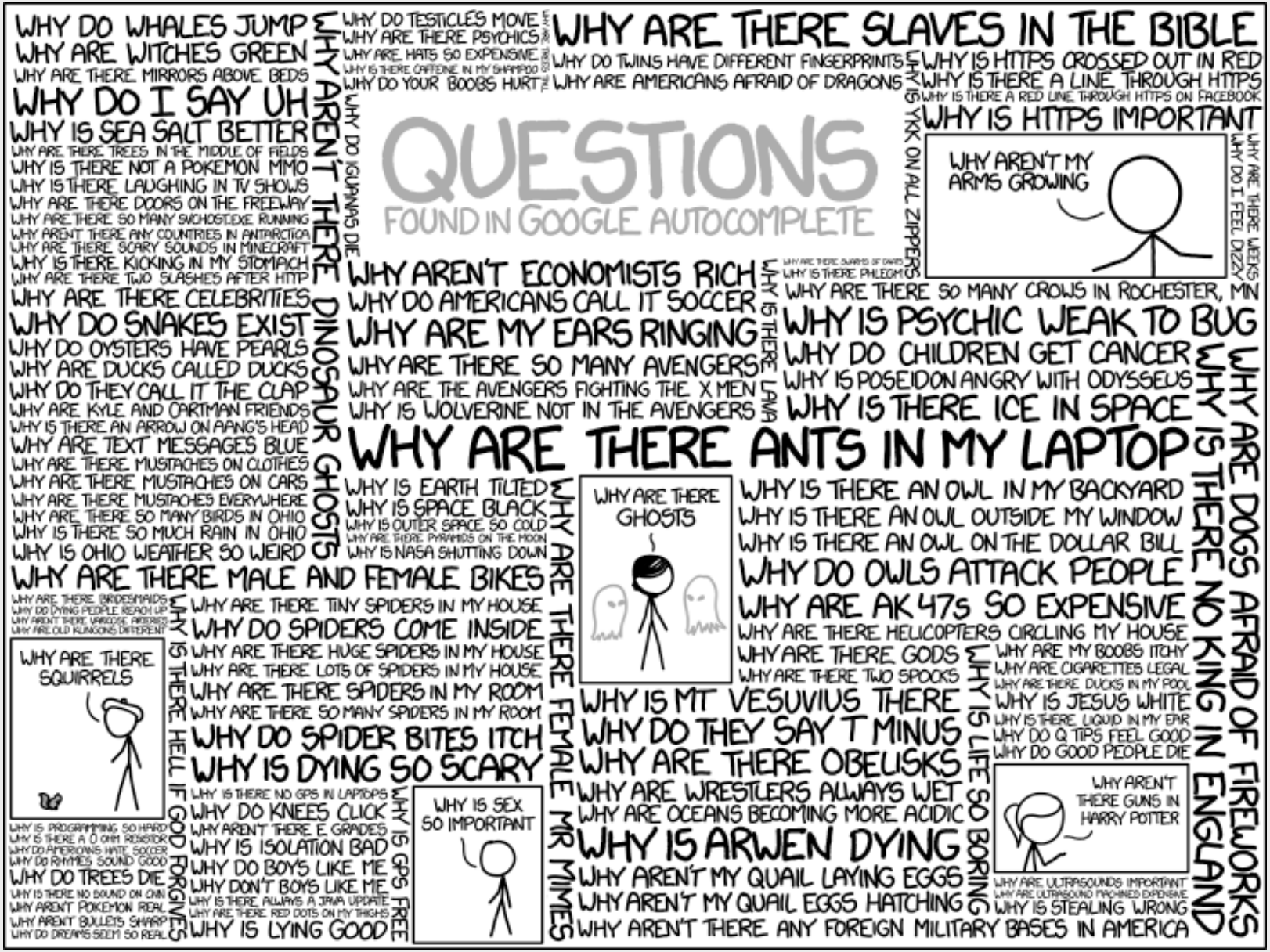
Takeaways

- There's a lot going on in these TGs
  - Precision Experiments:
    - EDMs
      - storage ring EDMs should be studied
    - *AMO connection (more than EDMs)*
  - CLFV, both inside and outside muons, is very popular: x10-100 increases in $\mu's$ and $\tau's$
  - *Strong Interest for a World Class CLFV/MDM/μSR muon program at PIP-II?*

Stay Tuned!

- These two topical groups, precision experiments and charged lepton flavor violation, are full of exciting new ideas
- They relate to each other and across all of Snowmass!
  - probe mass scales far beyond direct reach of colliders and attack questions of fundamental symmetries and the generation puzzle
- Several significant opportunities for world-class programs with multiple order-of-magnitude improvements

so much has been done,
and perhaps we have a glimpse of what is ahead


QUESTIONS
FOUND IN GOOGLE AUTOCOMPLETE
WHY DO WHALES JUMP
WHY ARE WITCHES GREEN
WHY ARE THERE MIRRORS ABOVE BEDS
WHY DO I SAY UH
WHY IS SEA SALT BETTER
WHY ARE THERE TREES IN THE MIDDLE OF FIELDS
WHY IS THERE NOT A POKEMON MMO
WHY IS THERE LAUGHING IN TV SHOWS
WHY ARE THERE DOORS ON THE FREEWAY
WHY ARE THERE SO MANY SVCHOST.EXE RUNNING
WHY AREN'T THERE ANY COUNTRIES IN ANTARCTICA
WHY ARE THERE SCARY SOUNDS IN MINECRAFT
WHY IS THERE KICKING IN MY STOMACH
WHY ARE THERE TWO SLASHES AFTER HTTP
WHY ARE THERE CELEBRITIES
WHY DO SNAKES EXIST
WHY DO OYSTERS HAVE PEARLS
WHY ARE DUCKS CALLED DUCKS
WHY DO THEY CALL IT THE CLAP
WHY ARE KYLE AND CARTMAN FRIENDS
WHY IS THERE AN ARROW ON AANG'S HEAD
WHY ARE TEXT MESSAGES BLUE
WHY ARE THERE MUSTACHES ON CLOTHES
WHY ARE THERE MUSTACHES ON CARS
WHY ARE THERE MUSTACHES EVERYWHERE
WHY ARE THERE SO MANY BIRDS IN OHIO
WHY IS THERE SO MUCH RAIN IN OHIO
WHY IS OHIO WEATHER SO WEIRD
WHY ARE THERE MALE AND FEMALE BIKES
WHY ARE THERE BRIDESMAIDS
WHY DO DYING PEOPLE REACH UP
WHY AREN'T THERE VARICOSE ARTERIES
WHY ARE OLD KLINGONS DIFFERENT
WHY ARE THERE SQUIRRELS
WHY IS PROGRAMMING SO HARD
WHY IS THERE A 0 OHM RESISTOR
WHY DO AMERICANS HATE SOCCER
WHY DO RHYMES SOUND GOOD
WHY DO TREES DIE
WHY IS THERE NO SOUND ON CNN
WHY AREN'T POKEMON REAL
WHY AREN'T BULLETS SHARP
WHY DO DREAMS SEEM SO REAL
WHY DO IGUANAS DIE
WHY DINOSAUR GHOSTS
WHY IS THERE HELL IF GOD FORGIVES
WHY DO TESTICLES MOVE
WHY ARE THERE PSYCHICS
WHY ARE HATS SO EXPENSIVE
WHY IS THERE CAFFEINE IN MY SHAMPOO
WHY DO YOUR BOOBS HURT
WHY ARE THERE SLAVES IN THE BIBLE
WHY DO TWINS HAVE DIFFERENT FINGERPRINTS
WHY ARE AMERICANS AFRAID OF DRAGONS
WHY AREN'T ECONOMISTS RICH
WHY DO AMERICANS CALL IT SOCCER
WHY ARE MY EARS RINGING
WHY ARE THERE SO MANY AVENGERS
WHY ARE THE AVENGERS FIGHTING THE X MEN
WHY IS WOLVERINE NOT IN THE AVENGERS
WHY ARE THERE ANTS IN MY LAPTOP
WHY IS EARTH TILTED
WHY IS SPACE BLACK
WHY IS OUTER SPACE SO COLD
WHY ARE THERE PYRAMIDS ON THE MOON
WHY IS NASA SHUTTING DOWN
WHY ARE THERE TINY SPIDERS IN MY HOUSE
WHY DO SPIDERS COME INSIDE
WHY ARE THERE HUGE SPIDERS IN MY HOUSE
WHY ARE THERE LOTS OF SPIDERS IN MY HOUSE
WHY ARE THERE SPIDERS IN MY ROOM
WHY ARE THERE SO MANY SPIDERS IN MY ROOM
WHY DO SPIDER BITES ITCH
WHY IS DYING SO SCARY
WHY IS THERE NO GPS IN LAPTOPS
WHY DO KNEES CLICK
WHY AREN'T THERE E GRADES
WHY IS ISOLATION BAD
WHY DO BOYS LIKE ME
WHY DON'T BOYS LIKE ME
WHY IS THERE ALWAYS A JAVA UPDATE
WHY ARE THERE RED DOTS ON MY THIGHS
WHY IS LYING GOOD
WHY IS GPS FREE
WHY ARE THERE FEMALE MR MIMES
WHY IS SEX SO IMPORTANT
WHY ARE THERE GHOSTS
WHY IS THERE AN OWL IN MY BACKYARD
WHY IS THERE AN OWL OUTSIDE MY WINDOW
WHY IS THERE AN OWL ON THE DOLLAR BILL
WHY DO OWLS ATTACK PEOPLE
WHY ARE AK 47s SO EXPENSIVE
WHY ARE THERE HELICOPTERS CIRCLING MY HOUSE
WHY ARE THERE GODS
WHY ARE THERE TWO SPOOKS
WHY IS MT VESUVIUS THERE
WHY DO THEY SAY T MINUS
WHY ARE THERE OBELISKS
WHY ARE WRESTLERS ALWAYS WET
WHY ARE OCEANS BECOMING MORE ACIDIC
WHY IS ARWEN DYING
WHY AREN'T MY QUAIL LAYING EGGS
WHY AREN'T MY QUAIL EGGS HATCHING
WHY AREN'T THERE ANY FOREIGN MILITARY BASES IN AMERICA
WHY IS LIFE SO BORING
WHY IS YKK ON ALL ZIPPERS
WHY IS HTTPS CROSSED OUT IN RED
WHY IS THERE A LINE THROUGH HTTPS
WHY IS THERE A RED LINE THROUGH HTTPS ON FACEBOOK
WHY IS HTTPS IMPORTANT
WHY AREN'T MY ARMS GROWING
WHY ARE THERE SWARMS OF DAYS
WHY IS THERE PHLEGM
WHY ARE THERE SO MANY CROWS IN ROCHESTER, MN
WHY IS PSYCHIC WEAK TO BUG
WHY DO CHILDREN GET CANCER
WHY IS POSEIDON ANGRY WITH ODYSSEUS
WHY IS THERE ICE IN SPACE
WHY IS THERE LAVA
WHY ARE MY BOOBS ITCHY
WHY ARE CIGARETTES LEGAL
WHY ARE THERE DUCKS IN MY POOL
WHY IS JESUS WHITE
WHY IS THERE LIQUID IN MY EAR
WHY DO Q TIPS FEEL GOOD
WHY DO GOOD PEOPLE DIE
WHY AREN'T THERE GUNS IN HARRY POTTER
WHY ARE ULTRASOUNDS IMPORTANT
WHY ARE ULTRASOUND MACHINES EXPENSIVE
WHY IS STEALING WRONG
WHY ARE THERE WEEKS
WHY DO I FEEL DIZZY
WHY IS THERE NO KING IN ENGLAND
WHY ARE DOGS AFRAID OF FIREWORKS